Power Supply Design Seminar

Topic 1 Presentation:

High Power Factor and High Efficiency — You Can Have Both

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TEXAS INSTRUMENTS

Topic 1

High Power Factor and High Efficiency: You Can Have Both

Isaac Cohen and Bing Lu

Agenda

- Definition of power factor and discussion of the applicable standards
- Effect of the power factor on power-distribution losses
- Benefits of active PFC
- Effect of the input-voltage range on PFC efficiency
- Configurable PFC topologies
- The buck PFC: a solution for universal input-voltage applications
- Conclusions

Definition of Power Factor: A Quick Review

- PF = Real Power / Apparent Power
- Real Power = $\frac{1}{T}\int_0^T vi\,dt$
- Apparent Power = $V_{RMS} \times I_{RMS}$
- Definition valid for arbitrary current and voltage waveforms

Linear and Nonlinear Loads

- Sinusoidal source, linear load
  - Both the voltage and the current are sinusoidal but not in phase; power factor less than unity
  - PF known as : cos(Φ) or “displacement power factor”
- Sinusoidal source, nonlinear load
  - PF is determined by phase angle and harmonics
  - Harmonics increase apparent power, the power factor also less than unity
  - Reducing harmonics increases the power factor

Standards for Power-Factor Correction

- EN61000-3-2
  - Focuses on line-current harmonics
  - Four categories according to different end equipments
  - Most power supplies are Class D
- Energy Star®
  - Power supplies with greater than or equal to 100-W input power must have a true power factor of 0.9 or greater at 100% of rated load when tested at 115 V, 60 Hz
- Universal-input power supplies need to meet requirements of both standards

Power Factor and EN61000-3-2 Class D

- Meeting EN61000-3-2 harmonic standard is not enough to meet the Energy Star power-factor requirement

Harmonic Order n	75 W < P < 600 W Maximum Permissible Harmonic Current (mA/W)
3	3.4
5	1.9
7	1.0
9	0.5
11	0.35
13	0.269
15 ≤ n ≤ 39	3.85/n

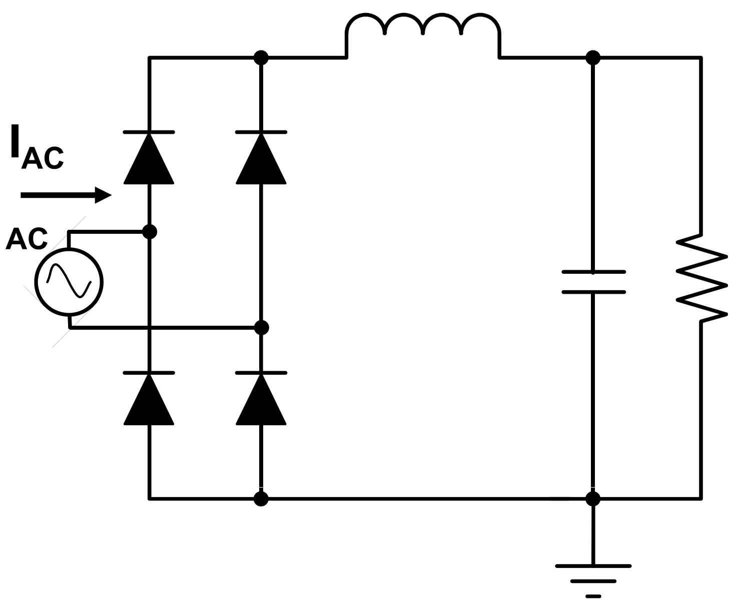
$$PF = F_{Displacement} \times F_{Distortion}$$

$$F_{Displacement} = 1$$

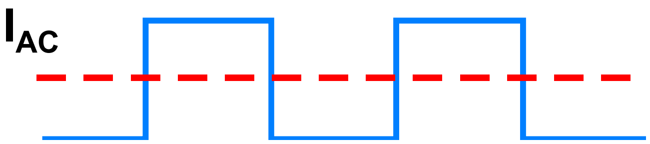
$$PF = \frac{I_1}{\sqrt{\sum_{n=1,3}^{39} {I_n}^2}} = 0.726$$

Harmonics for Energy Star

- A power supply drawing square-wave line current is well within Energy Star PF limits but will fail the IEC harmonic-content standard



$$PF = 0.9$$



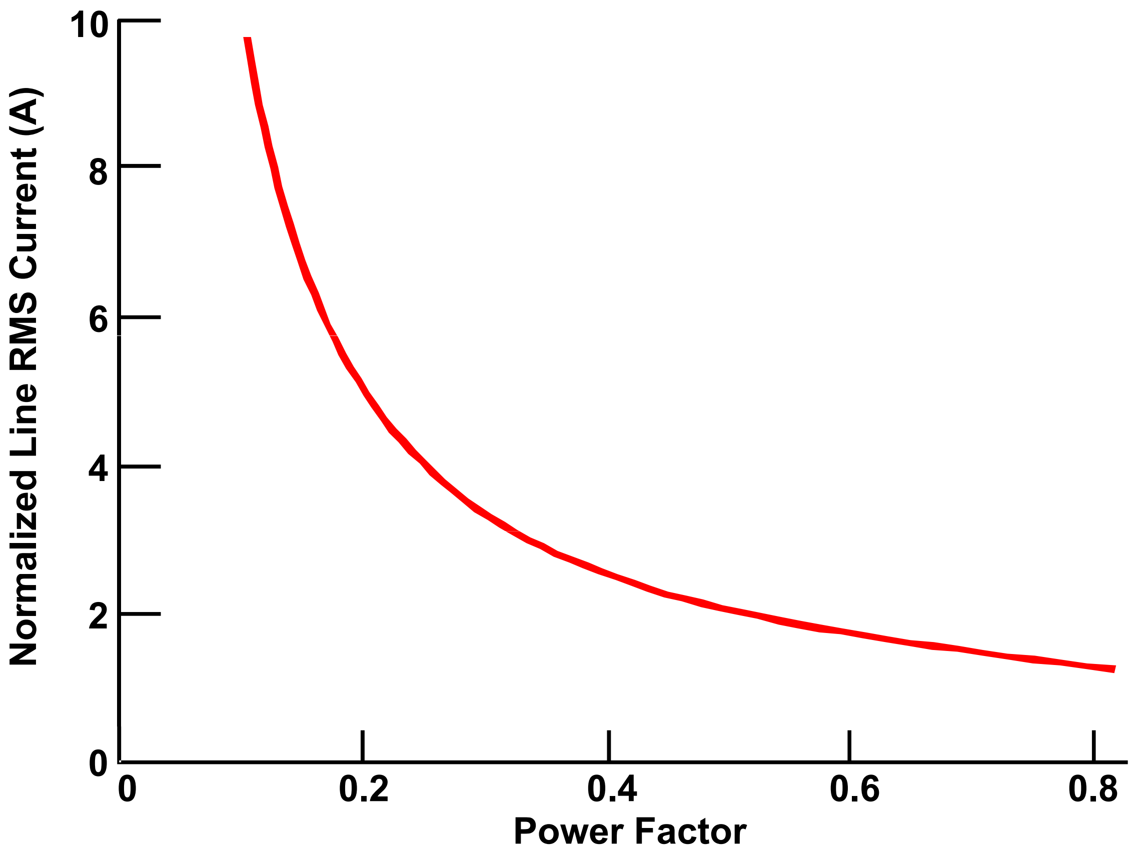
$$I_{11} = 0.56 \text{ mA / W} > 0.35 \text{ mA / W}$$

Meeting Both Standards

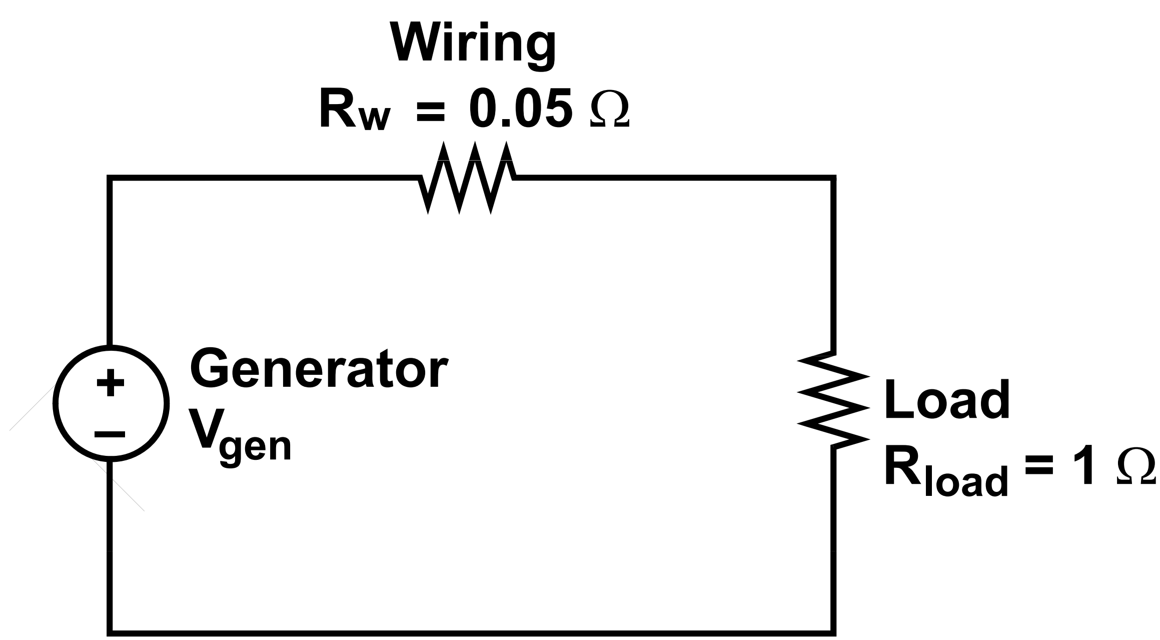
- The PFC circuit must increase the PF to the Energy Star limit **AND** attenuate the harmonics below the limits of EN61000-3-2

The Power Factor and the Power-Distribution Losses

- If the PF is low, an increase in RMS current is required to deliver a given amount of power



Normalized Power-Distribution Losses

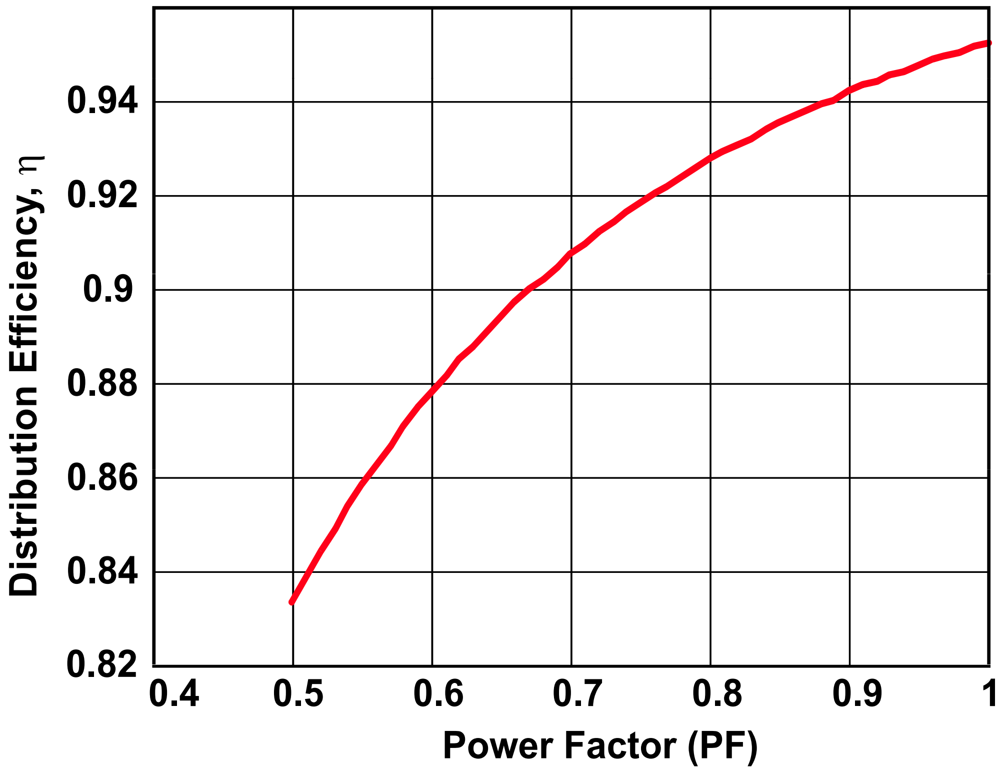


Where:

V_{gen} = Effective AC source voltage
R_w = Distribution wiring resistance
R_{load} = Load resistance

Effect of the Power Factor on Power-Distribution Losses

- PFC reduces distribution losses
- Assuming 5% distribution loss, the system will break even if the efficiency of the PFC circuit is 0.953



Direct Benefits of PFC/Harmonics Attenuation

- Meet the requirements of EN61000-2-3 and Energy Star
- Higher power factor
- Allows higher power draw from 115-V lines
  - 0.5 PF = 719 W,   0.9 PF = 1294 W (intermittent rating)
- Reduced stresses on neutral conductors
- Improved electrical system distribution efficiency (Only if the PFC efficiency is high enough!)
- Reduced VA rating of standby power systems

Indirect Benefits of Active PFC/Harmonics Attenuation

- Facilitates power supply holdup
- Universal input voltage capability (85 to 265 VAC)
- Improved efficiency of downstream DC/DC converters

Active PFC/Harmonic Attenuation Circuits

- Most popular active PFC circuit: The boost converter
- This additional conversion stage adds power dissipation
- **Efficiency of the PFC stage is strongly dependent on the difference between the input and the output voltage**

Analysis of the Boost PFC Efficiency

- To examine the effect of the difference between the input and output voltages on efficiency, we define the "Boost Factor" BF:

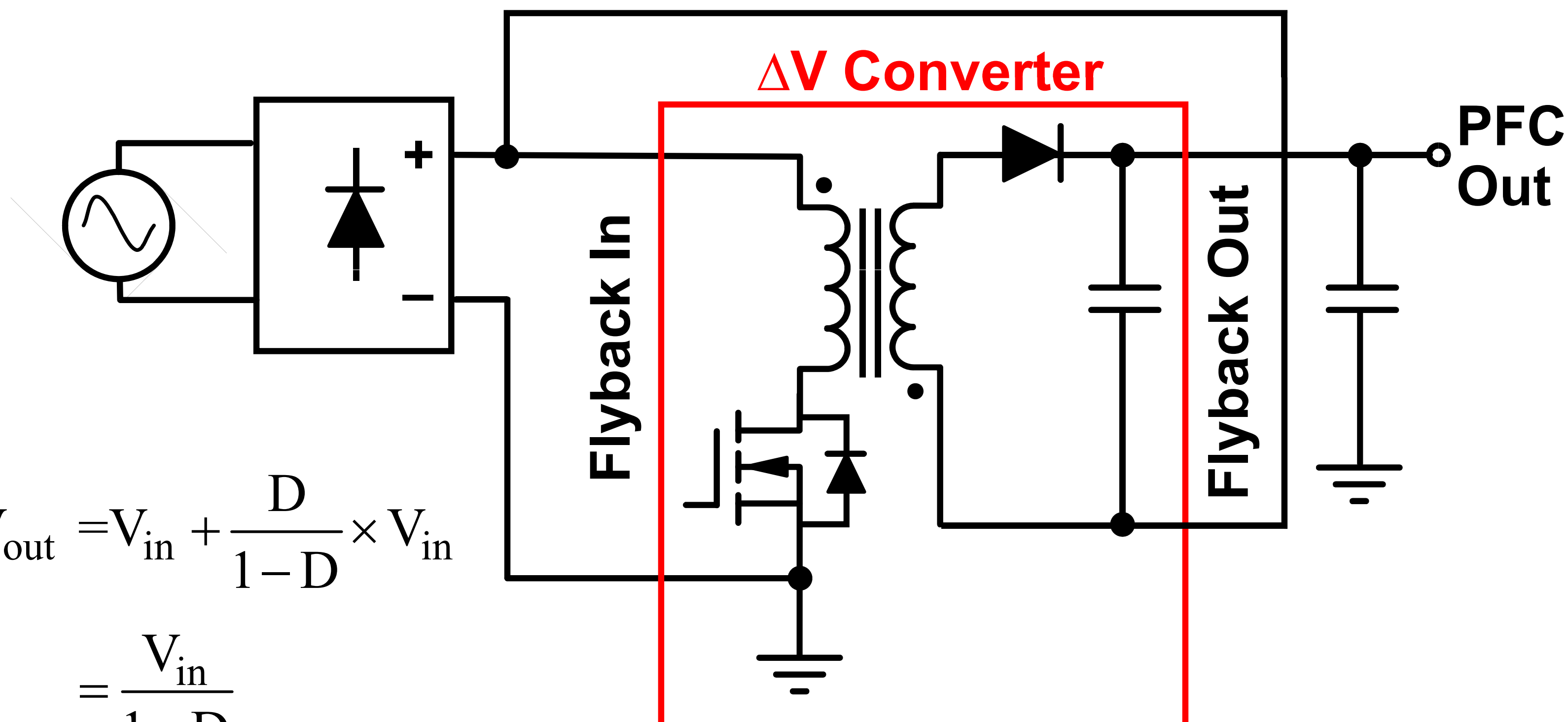
$$BF = \frac{V_{out}}{V_{in(pk)}}$$

Analysis of the Boost PFC Efficiency

- A nonisolated converter is similar to an autotransformer
- Separate the power flow by separating the power transferred directly to the output from power processed by the PFC circuit
- Emulate the PFC boost converter by adding the output of a flyback converter (“ΔV converter”) in series with the rectified line-input voltage
- The model is equivalent to a boost converter

The ΔV Converter

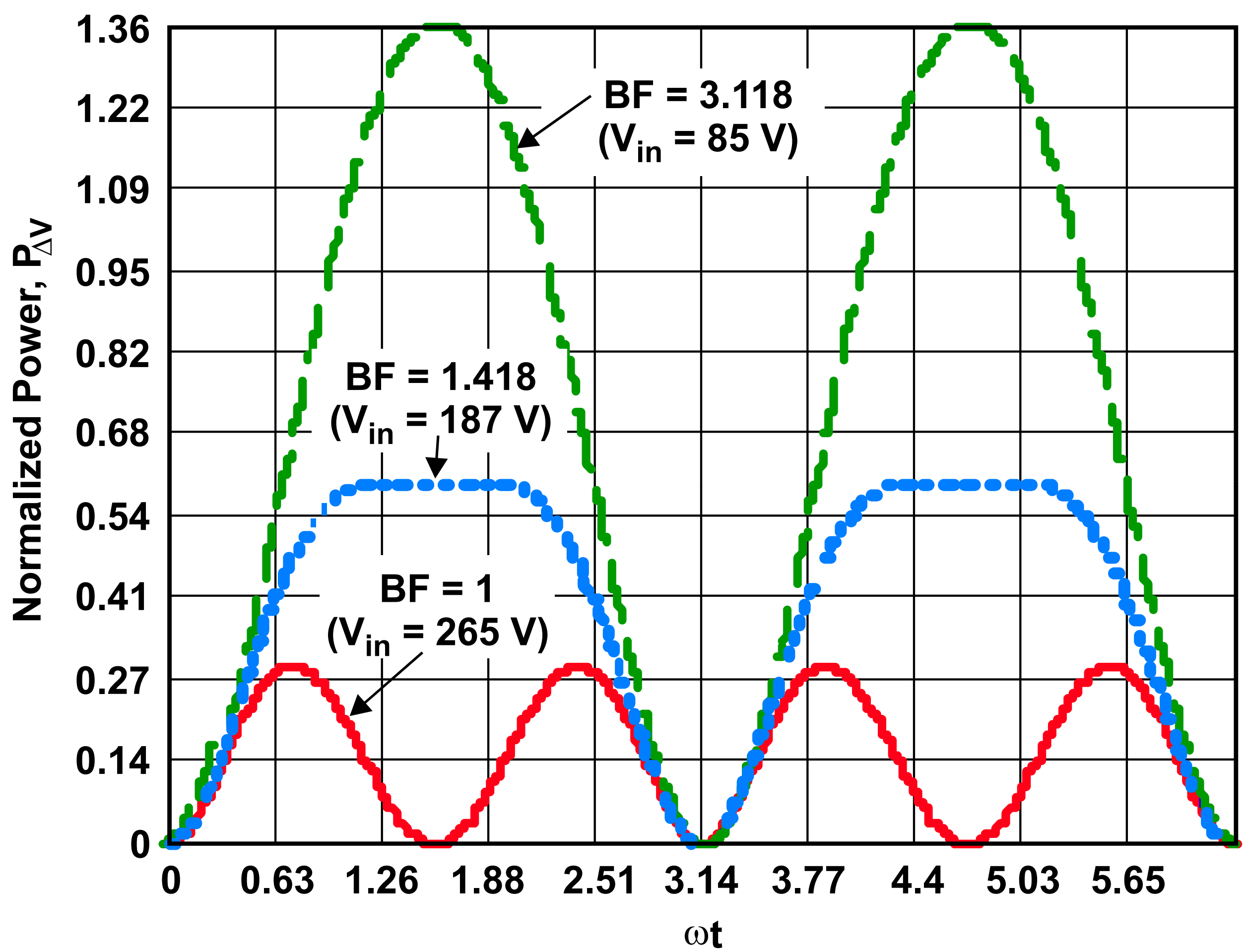
- A little algebra shows that the DC transfer function of the proposed circuit is identical to that of a boost converter



$$V_{out} = V_{in} + \frac{D}{1-D} \times V_{in}$$

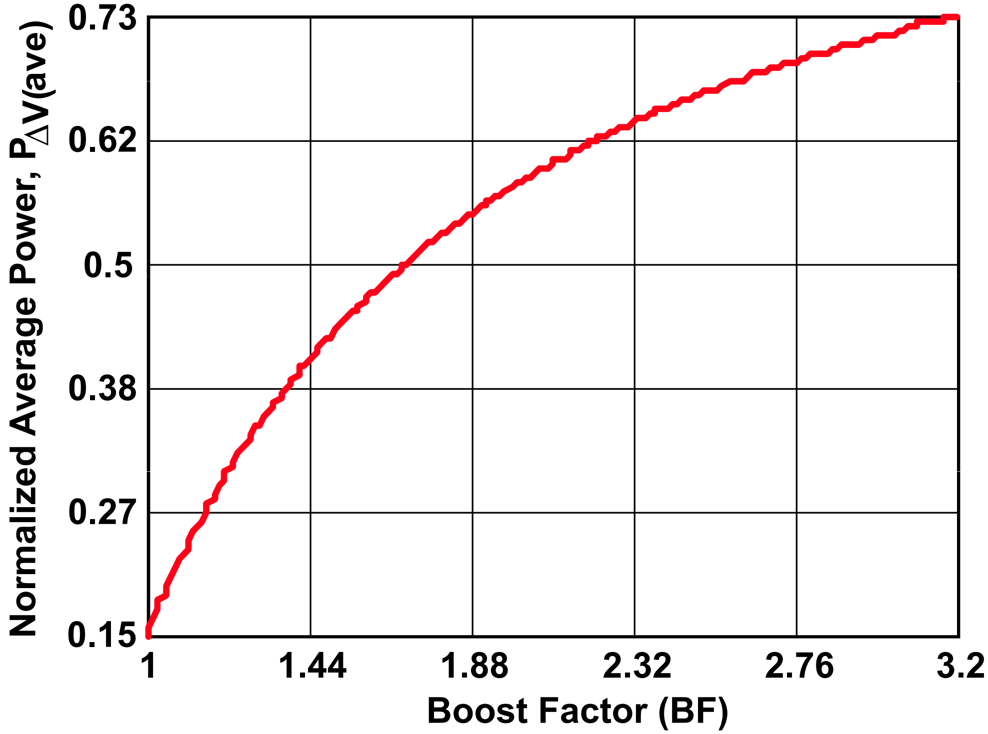
$$= \frac{V_{in}}{1-D}$$

Peak-Power Rating of the ΔV Converter as a Function of Input Voltage



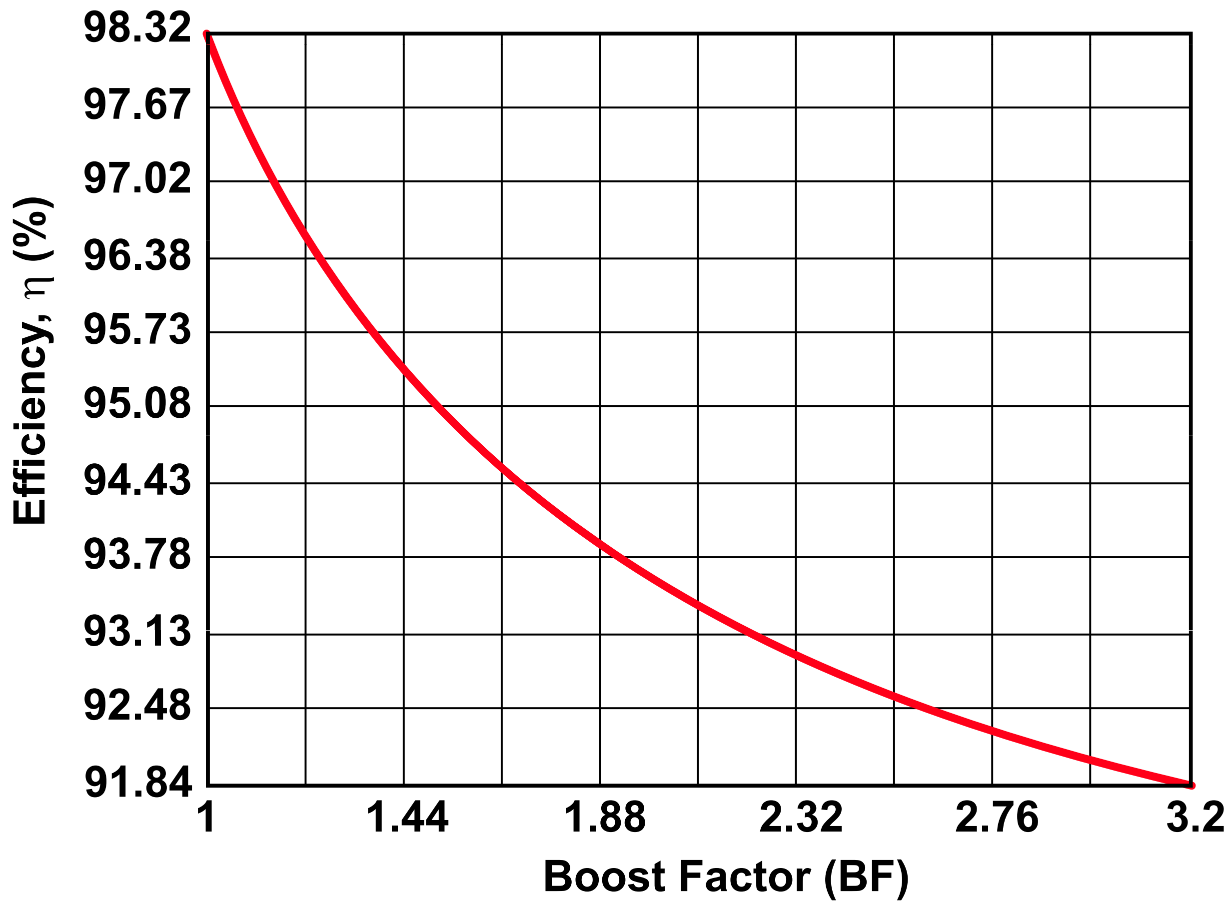
Average-Power Rating of ΔV Converter as a Function of Input Voltage

- The average power delivered by the ΔV converter is a strong function of BF
- An increasing BF also corresponds to an increase in boost-PFC size and cost



Overall PFC Efficiency versus BF

- ΔV converter efficiency = 90%



Discussion of the Results

- As the boost factor increases, the converter processes more power and the efficiency decreases
- Component ratings and converter efficiency are driven by the lowest operating Boost Factor
- For “local” voltages
  - Designed for Boost Factor of 1.417
  - ΔV-converter average- and peak-power ratings are 40.1% and 58.9% of the PFC-stage output power
- For universal input voltage
  - Designed for Boost Factor of 3.118
  - ΔV converter average- and peak-power ratings are 73% and 136% of the PFC-stage output power

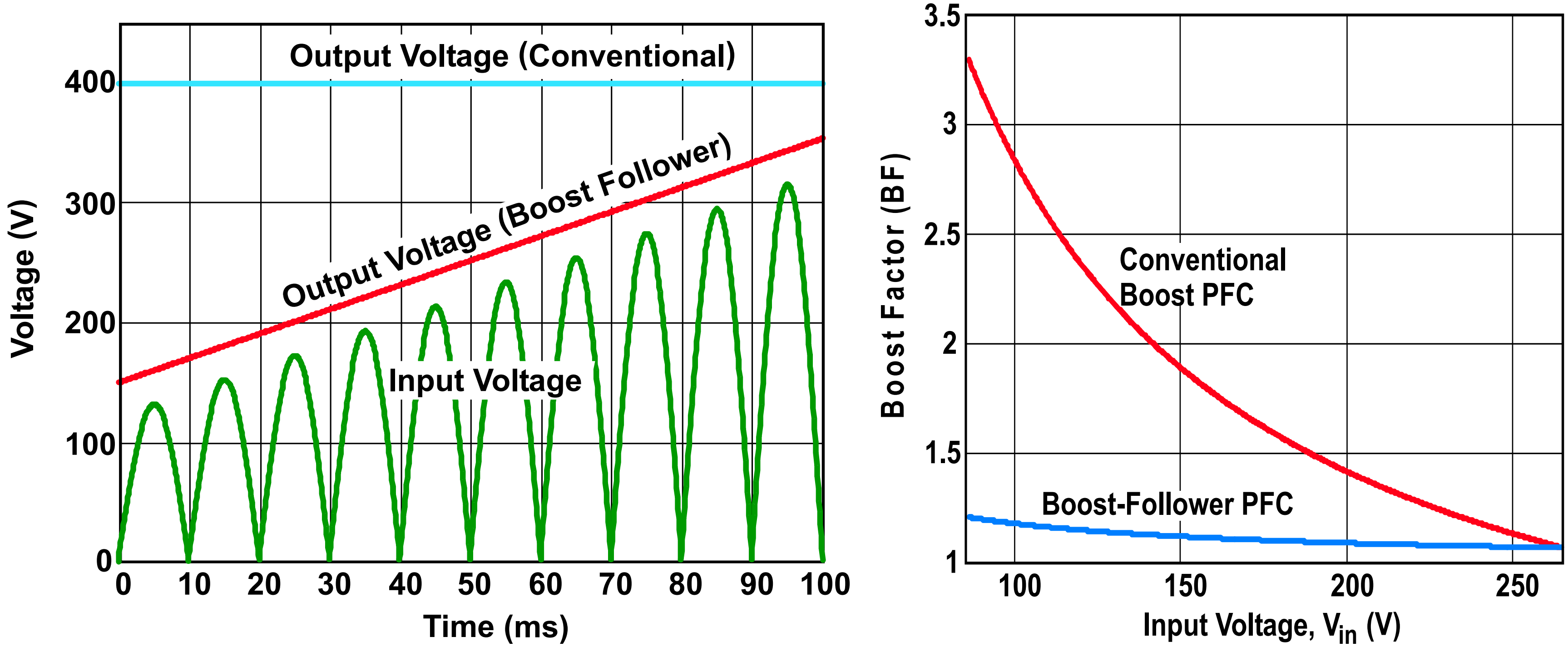
Universal-Input Voltage Issues

- Must or preference?
- Logistics, commonality
- "Regional" products
  - HVDC bus voltage
  - BOMs for the PFC converter and the downstream DC/DC converter(s)
- Trade-offs

Improving PFC Efficiency: Reduce Boost Factor!

- Ideas:
  - Boost follower
  - Configurable PFC stage
    - Three-level PFC
  - Buck instead of boost PFC

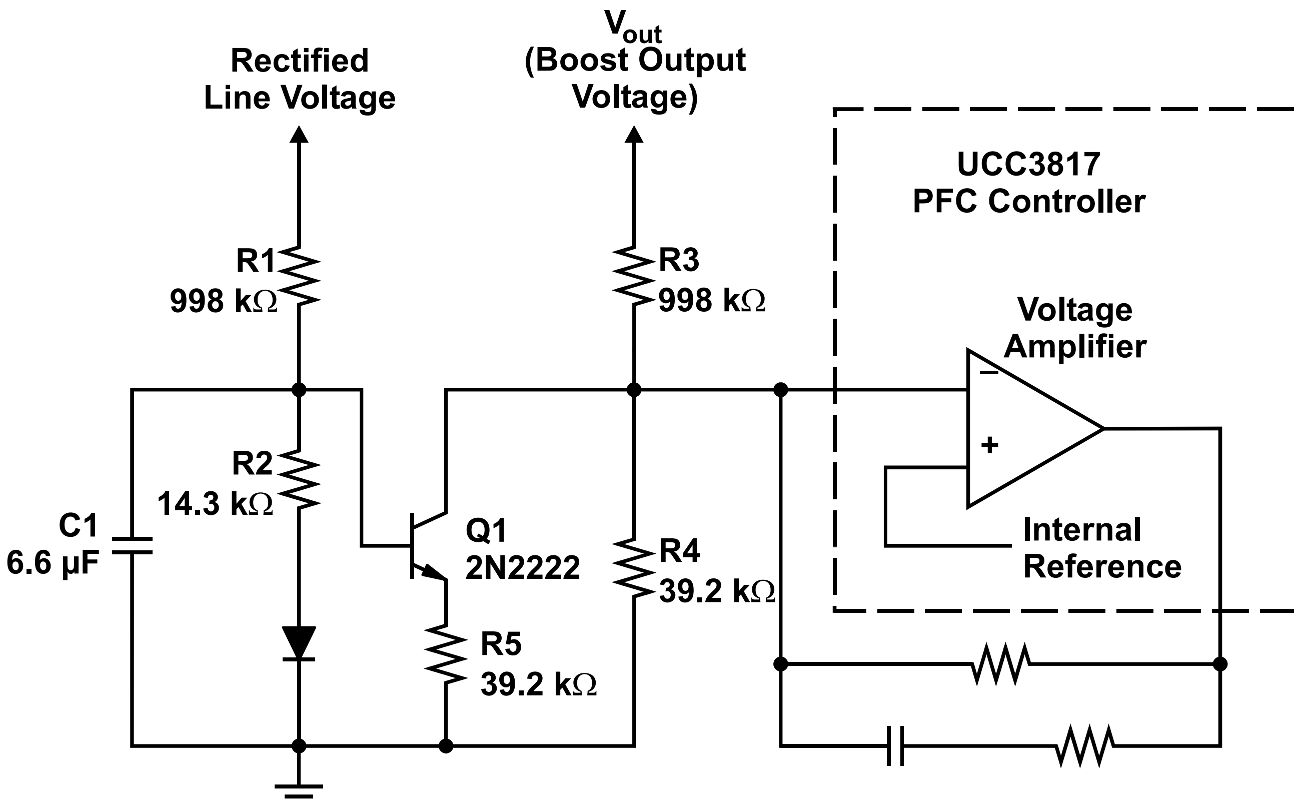
Boost-Follower PFC



- Conventional PFC maintains same output voltage for different line voltages, the boost factor is 3.3 at 85-V input
- Boost follower PFC changes its output voltage according to the AC line voltage (following AC line voltage)
- Boost factor is greatly reduced and efficiency can be improved but V_{out} is not constant

Boost-Follower PFC Implementation

- By adjusting the voltage-sensing divider network, output voltage can be changed with most off-the-shelf PFC controllers



"Simple circuitry gets that old PFC controller working in a boost-follower PFC Application," By Michael O'Loughlin

Design Considerations

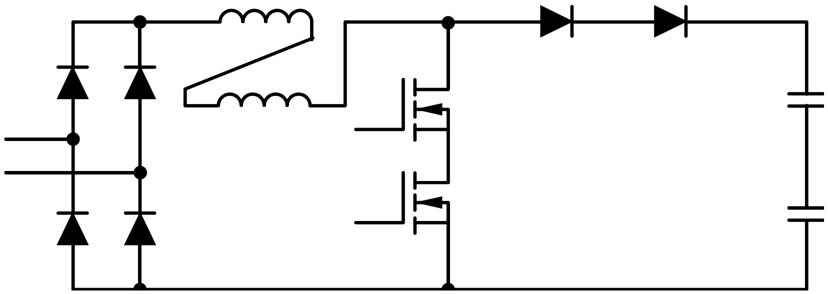
- "Boost Follower" reduces BF but:
  - Transformer turns ratio in the downstream converters must be lower, so:
    - Primary currents are higher, VA rating increases
    - Higher voltages on rectifiers, higher V_f
    - Larger filter inductor
    - Larger capacitors on the HV bus

Configurable Topologies

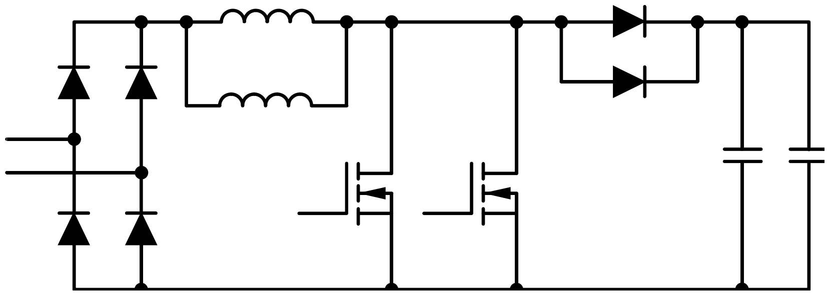
- Use identical components for both 115-V and 230-V inputs
- Same HVDC bus voltage
- Configuration on assembly line for 115 V or 230 V
- Nearly equal efficiencies for 115-V or 230-V operation

"Ideal" Configurable PFC

High line-input configuration

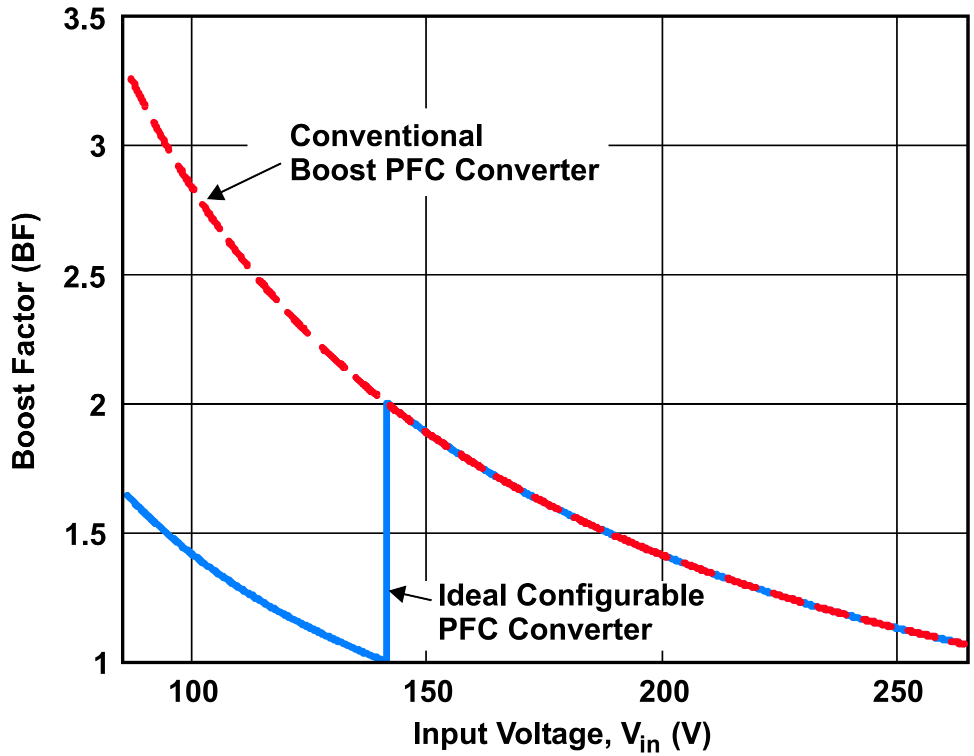


Low line-input configuration



- At high line input, the MOSFETs, diodes, and inductors are in series
- Output voltage is equal to the peak of the high line voltage (same as conventional PFC)
- At low line input, the MOSFETs, diodes, and inductors are in parallel
- Output voltage is only half the peak of the high line voltage
- Equal stresses on the converter components at either "High" or "Low" line-input configuration!

Boost Factor of Ideal Configurable PFC



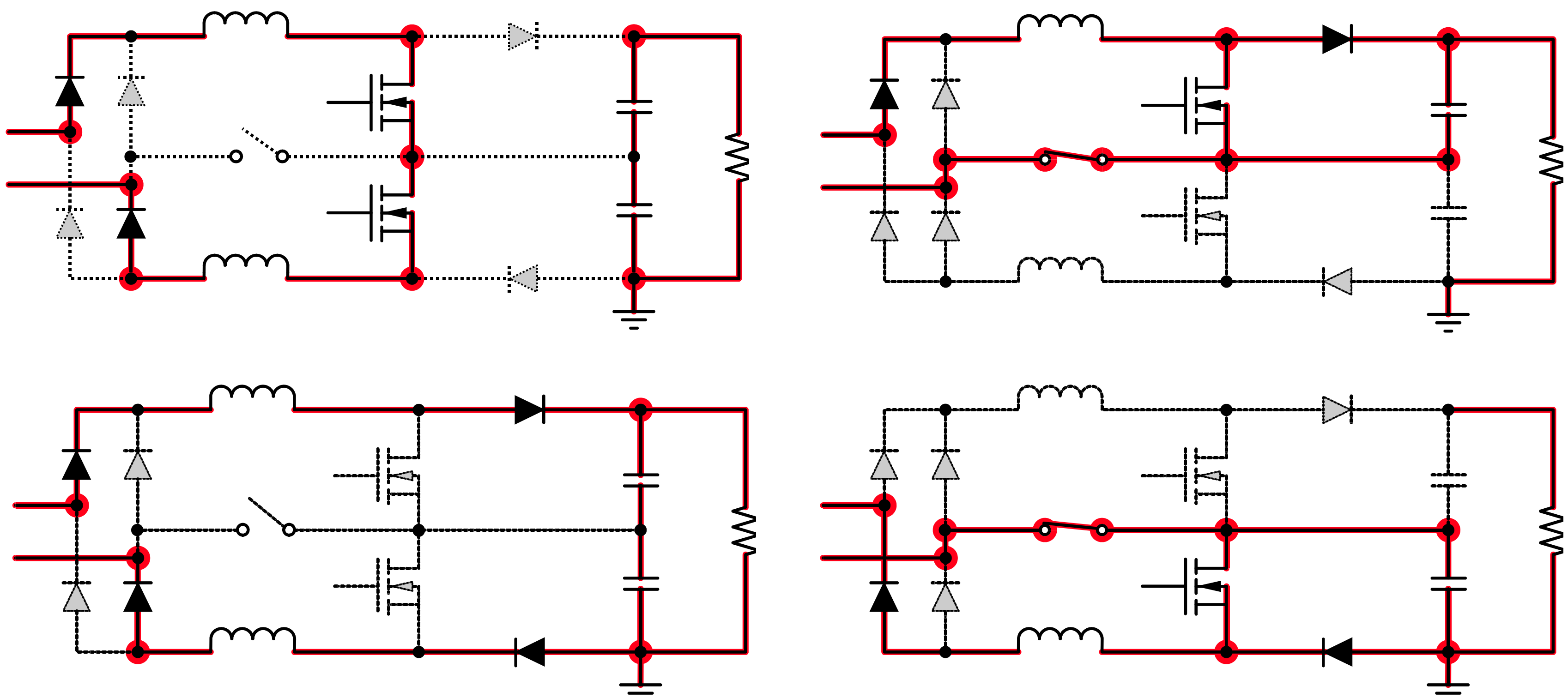
- At “high” line-input condition, the BF and the output voltage are the same as for a conventional PFC
- At “low” line-input condition, the BF and the output voltage are half the values of a conventional PFC

“Real-Life” Solutions

- The “ideal” circuit is not practical
  - Voltage balancing for series devices
  - Driving circuit for series circuits
- Practical circuits will be less efficient than the ideal

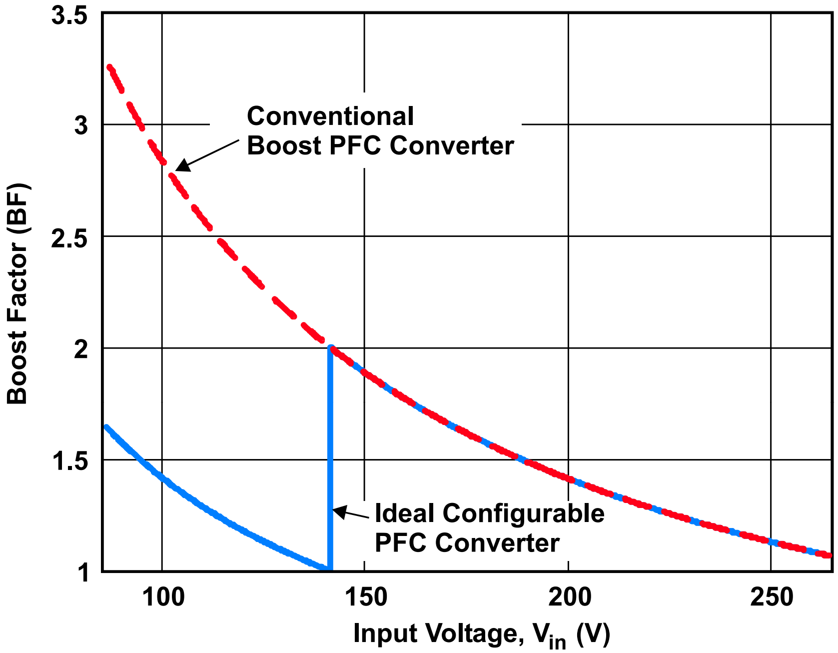
Configurable Three-Level PFC

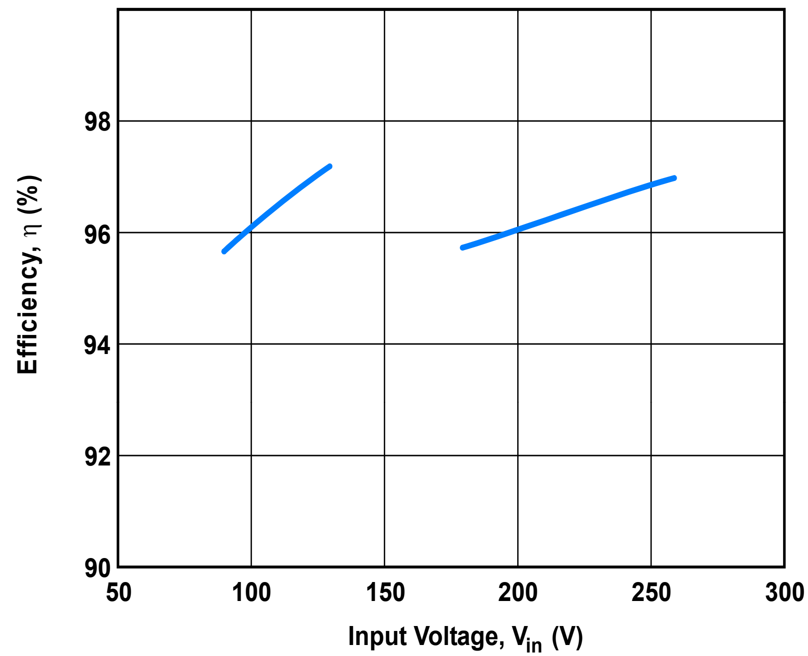
- High line-input condition: two boost PFCs are in series
- Low line-input condition: only one boost PFC is operating at each half line cycle



Note: Output-bus voltage does not change for different configurations

Boost Factor and Efficiency Estimation





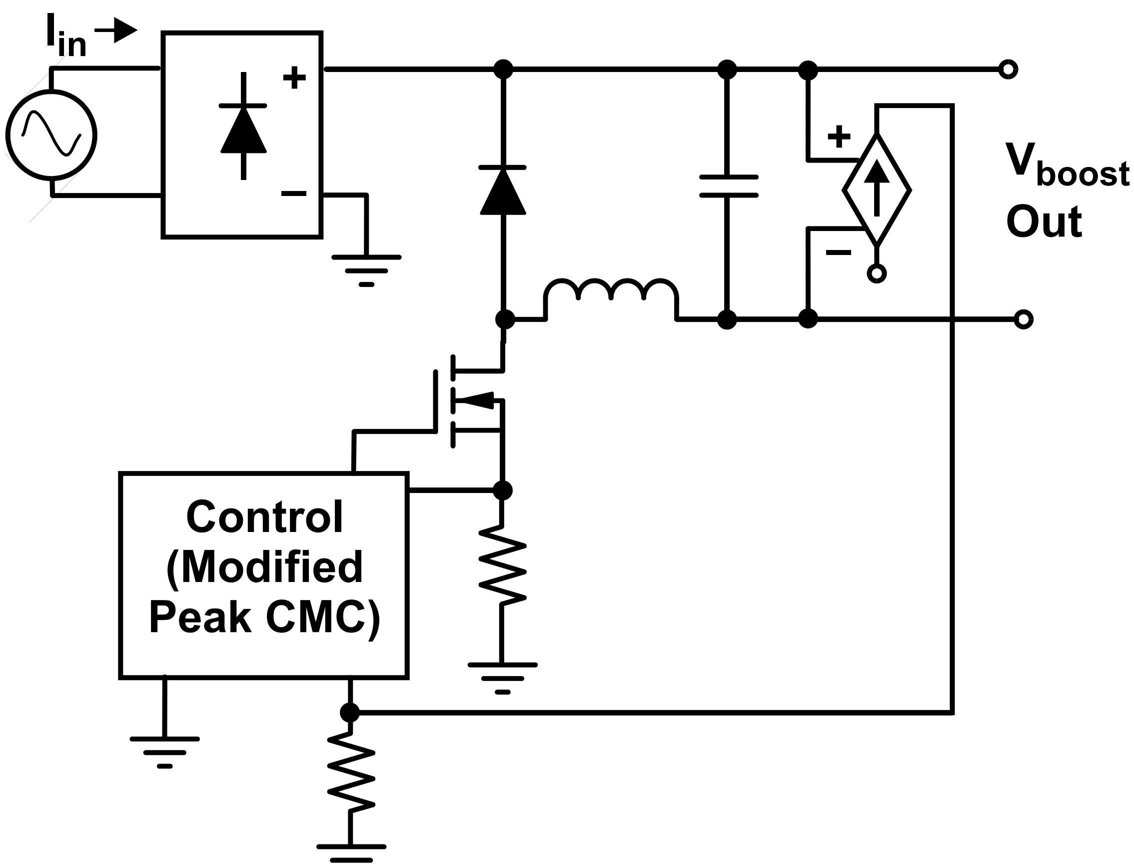
- Configurable three-level PFC maintains same output voltage for different line conditions
- At low line input, each boost PFC operates half-line cycle and the equivalent output voltage is half of the total PFC output voltage
- This reduced output voltage reduces the boost factor at low line input and improves efficiency

Benefits and Challenges

- Benefits
  - Reduced boost factor improves overall system efficiency
  - Three-level structure, a lower-voltage switches and diodes can be used to improve efficiency
  - At low line conditions, the bridge is reconfigured as a doubler (bridge diodes can be paralleled)
- Challenges
  - At low line input, each boost PFC only operates half of the line cycle (component utilization)
  - Devices referenced to different grounds: drive, current sensing
  - Voltage balancing on the output capacitors

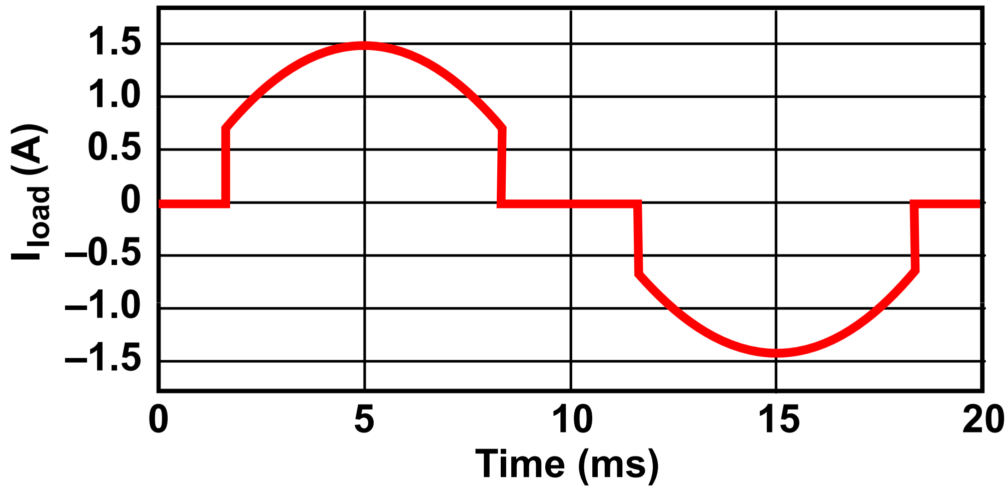
The Buck PFC

- A buck converter can also shape the input current
- Handles least power at lowest input ("Buck Factor")

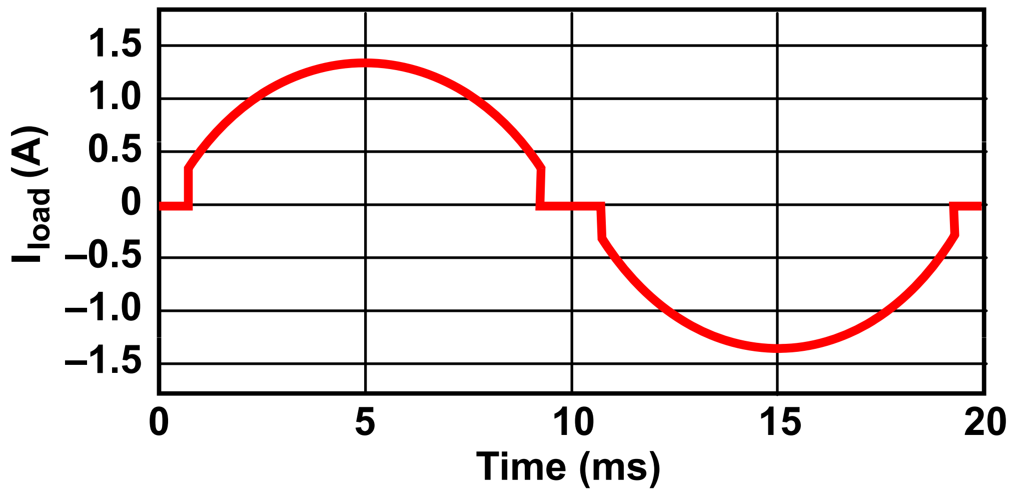


Idealized AC-Line Current with a Buck PFC

Low Line Input
(Normalized input current)



High Line Input
(Normalized input current)



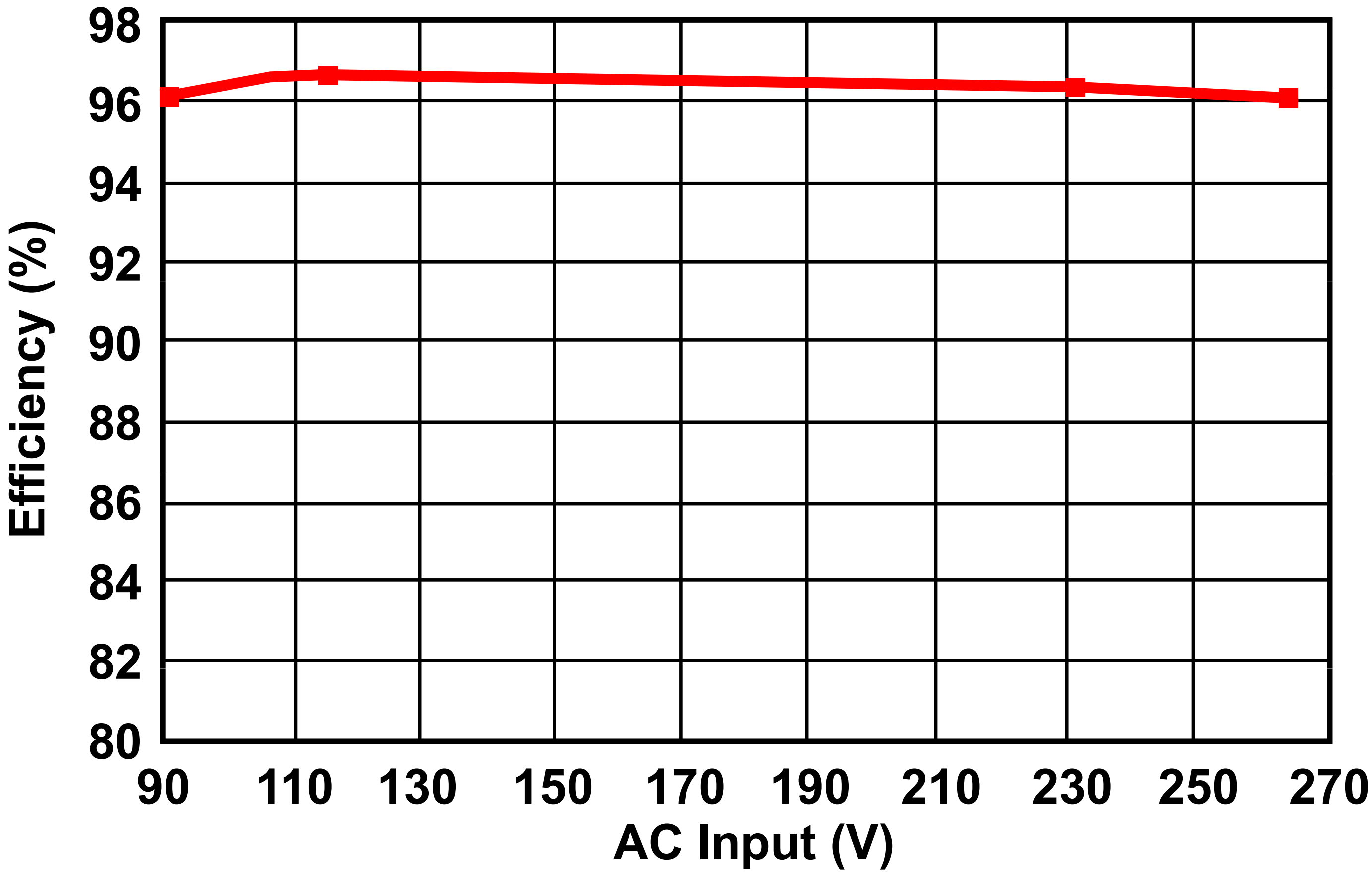
Buck PFC and Prevailing Standards

- The buck PFC draws current only if the input voltage is higher than the output voltage
- The optimal output voltage for universal input voltage is 80 V
- Waveform is “ugly” – but passes both EPA and IEC standards

Benefits of the Buck PFC

- Solves the problem of low efficiency at low input voltage
- Allows optimization of the downstream DC/DC converter
- Inherent inrush-current control
- "Gentler" on the HV diode than the boost converter it replaces

Efficiency of a 90-W Buck PFC versus the AC-Input Voltage



Conclusions

- PFC provides many benefits but adds losses that are strongly affected by the Boost Factor
- Reconfigurable-PFC topology is available that can reduce the effective BF and use the same components for both 115-V and 230-V lines—others to be invented?
- It remains to be seen if the pressure for ever higher efficiency will drive adoption of more complex topologies
- The buck PFC is an attractive solution for universal input voltages at power levels below 600 W

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Email	tiasia@ti.com or ti-china@ti.com
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